

# Using Heavy Ions (Pb+Pb) to Search for New forms of QCD matter at LHC

Can the sQGP shed light on its Glasma embryo?



"Que Sera, Sera "

(Whatever Will Be, Will Be)"

Miklos Gyulassy  
Columbia

**Glasma?**

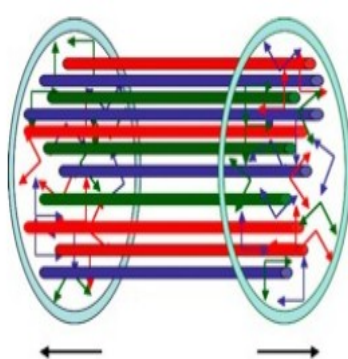


**Plasma?**

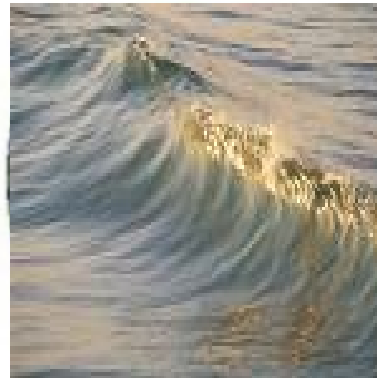
Why is Predicting the Future so hard?

$t = -\infty$  $t = 0$  $t = 1 \text{ fm}/c$  $t = 3-7 \text{ fm}/c$  $t = +\infty$ 

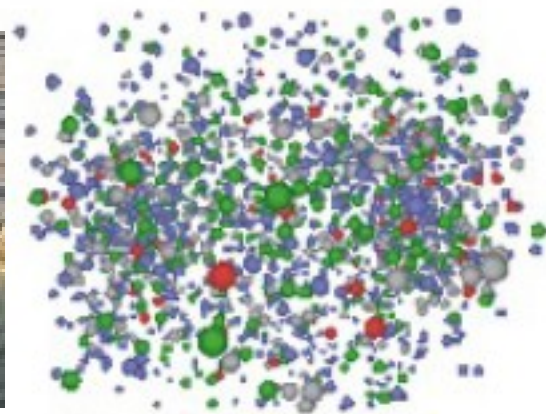
CGC

Initial  
Singularity

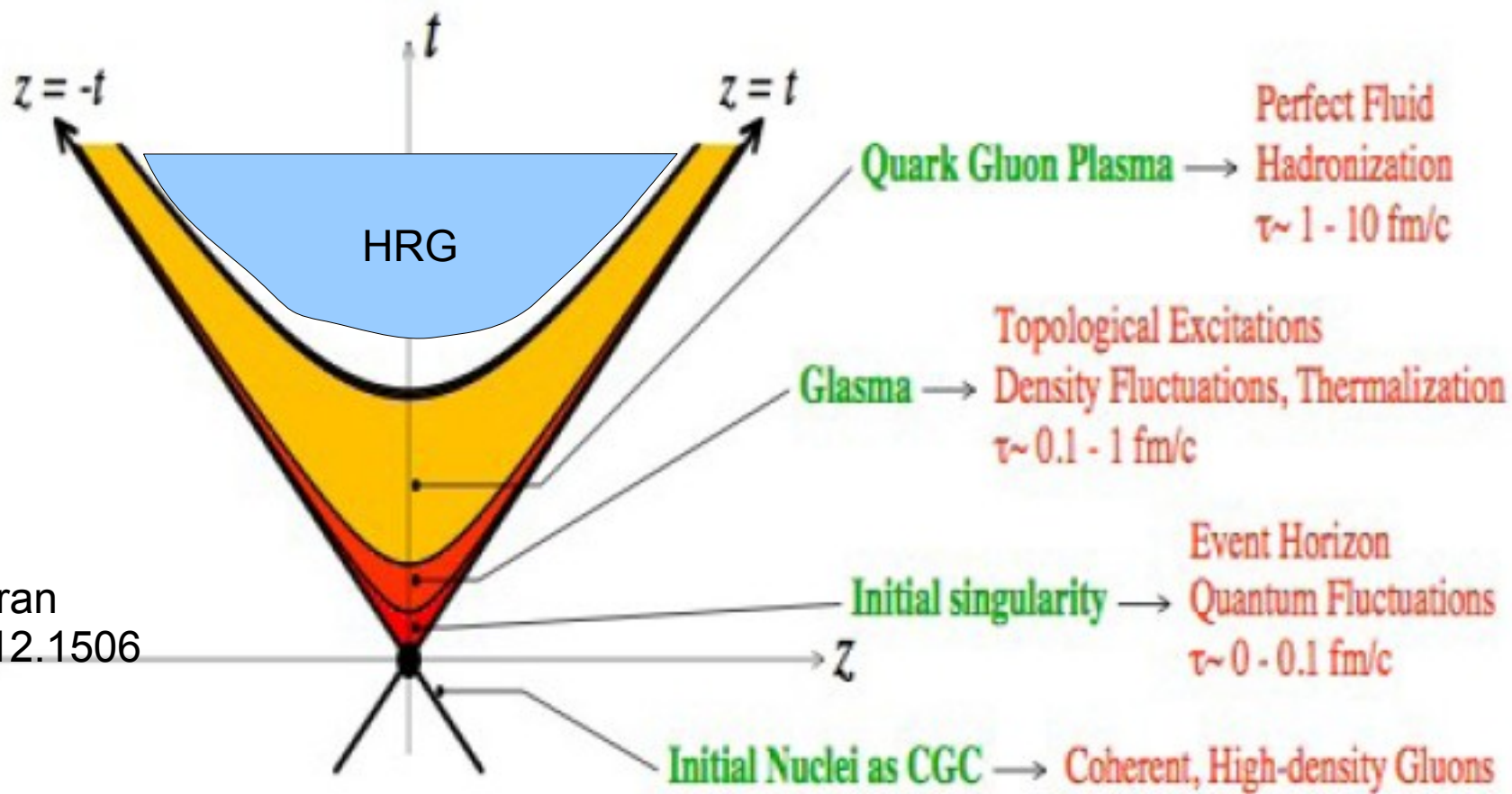
Glasma



sQGP



Hadron Gas



L. McLerran  
arXiv:0812.1506

## Some LHC Challenges

Part 1: Why are LHC initial conditions so hard to predict?

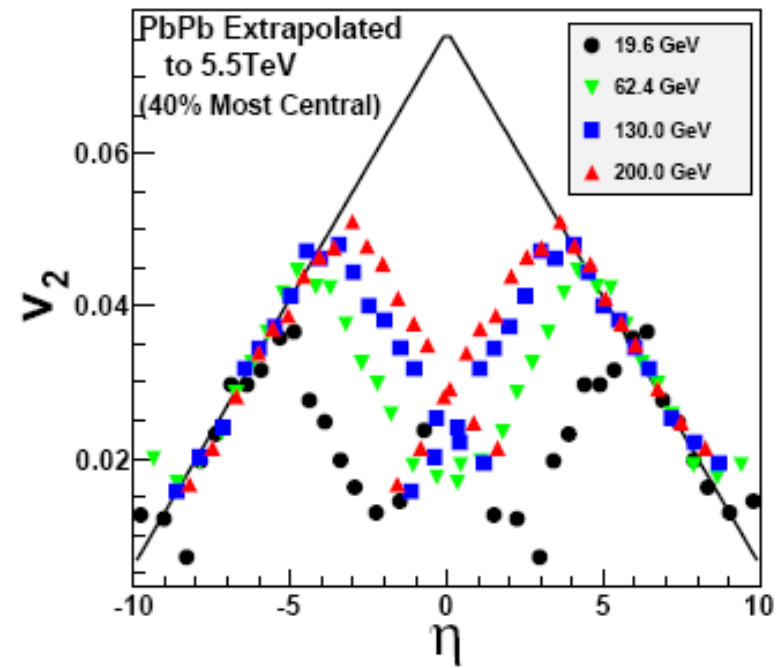
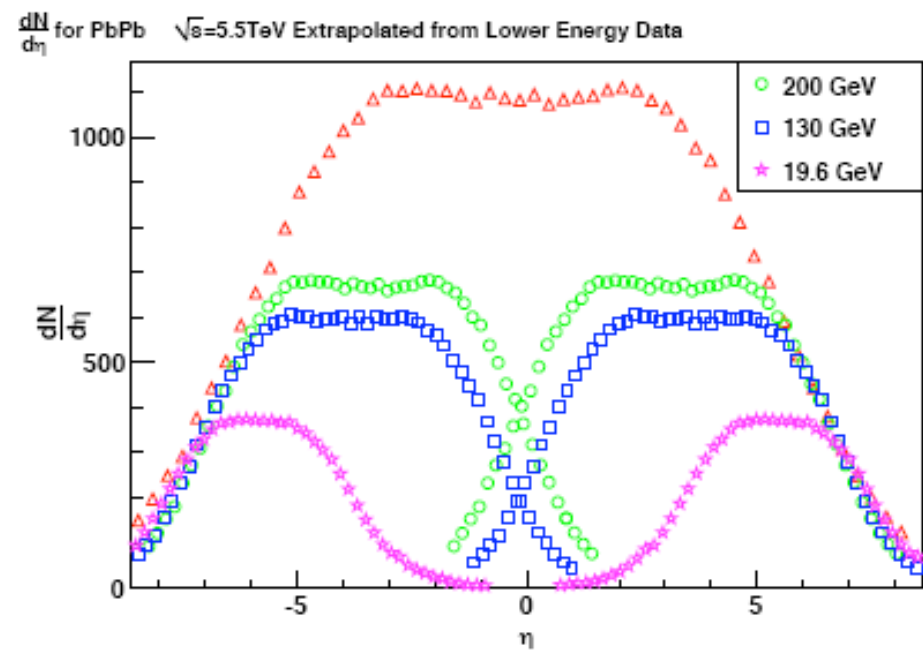
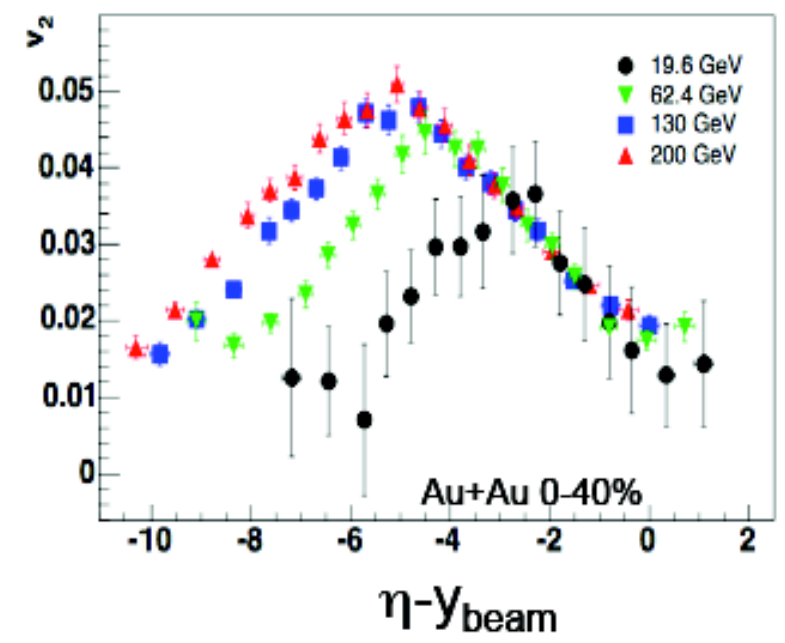
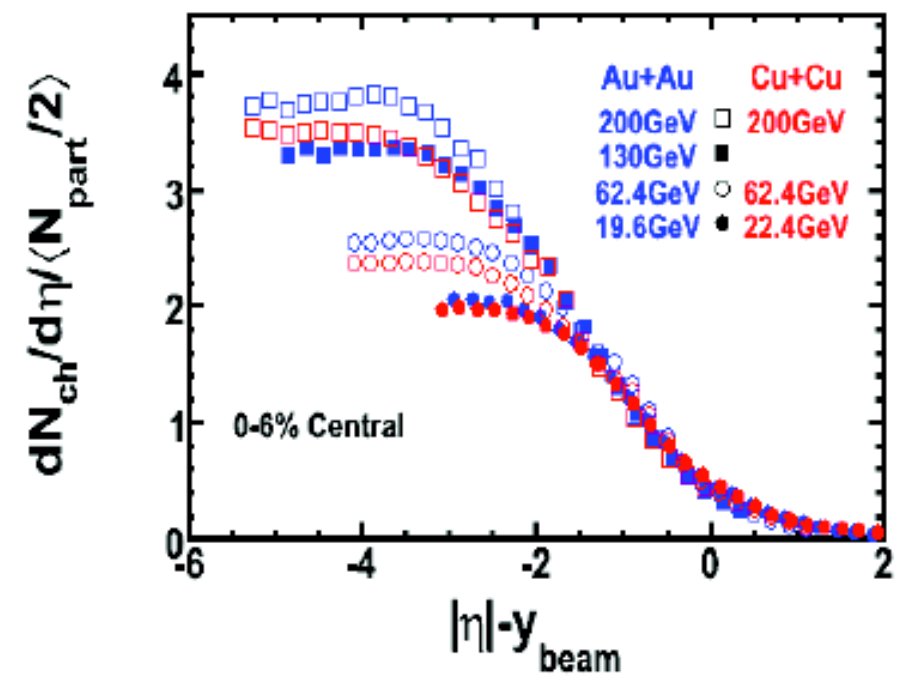
Part 2: Will Perfect Fluidity evolve into “Divine” Flow at LHC?

Part 3: Will the Glasma solve the (possible)  
breakdown of sQGP hydro at LHC?

Part 4: Will we be able to deconvolute the Glasma quenching  
from final state Plasma quenching via pA at LHC?

We only have six months to Predict new physics  
and put new ideas on the LHC butcher block

# Busza's Ruler Systematics = linear Log(s),Log(A) physics from AGS->LHC



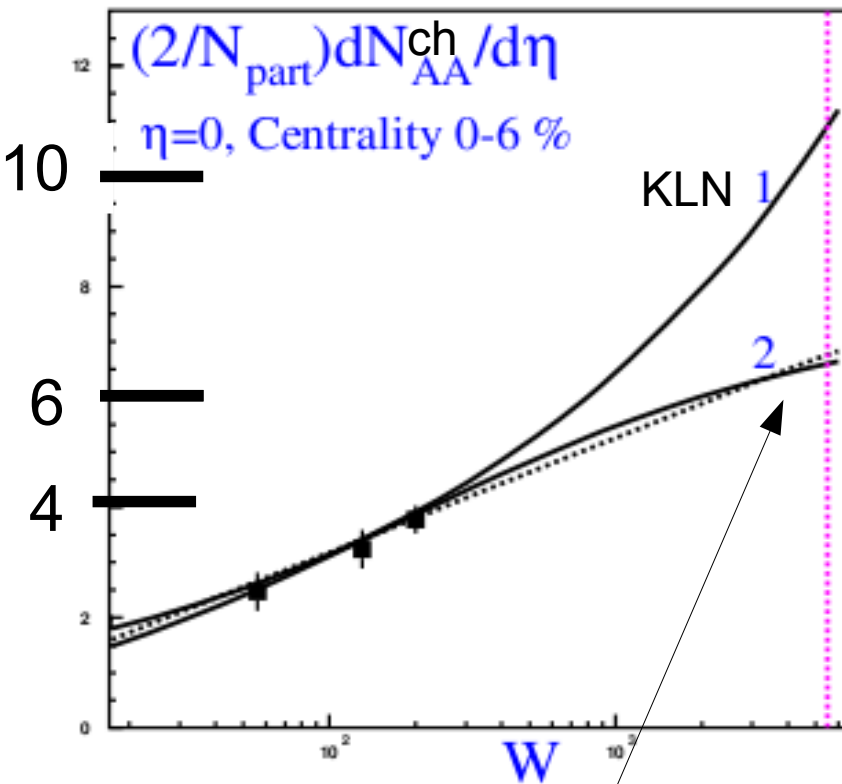
State of the Color Glass Art is nonlinear with

1.18. Hadron multiplicities at the LHC

$dN^{\text{ch}}/dY$  variations 1000- 2000

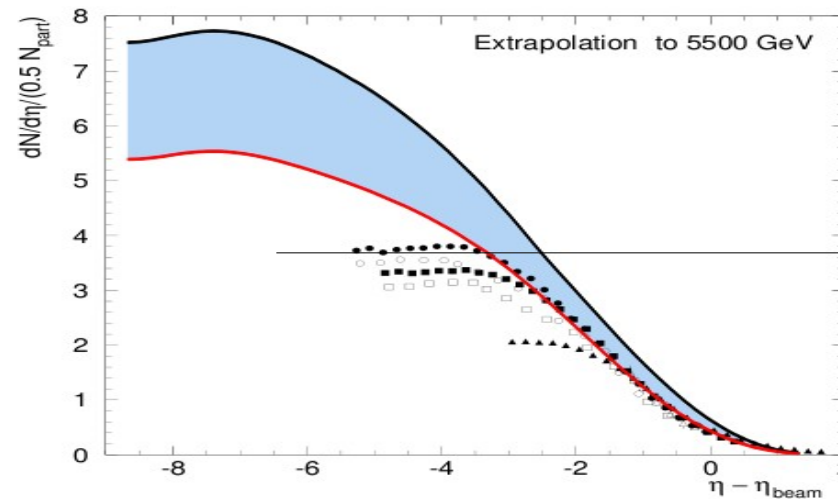
D. Kharzeev, E. M. Levin and M. Nardi

50% Uncertainty on Initial Cond.



MV vs GBW models fit to RHIC evolved BK  
1.15. Melting the Color Glass Condensate at the LHC

H. Fujii, F. Gelis, A. Stasto and R. Venugopalan

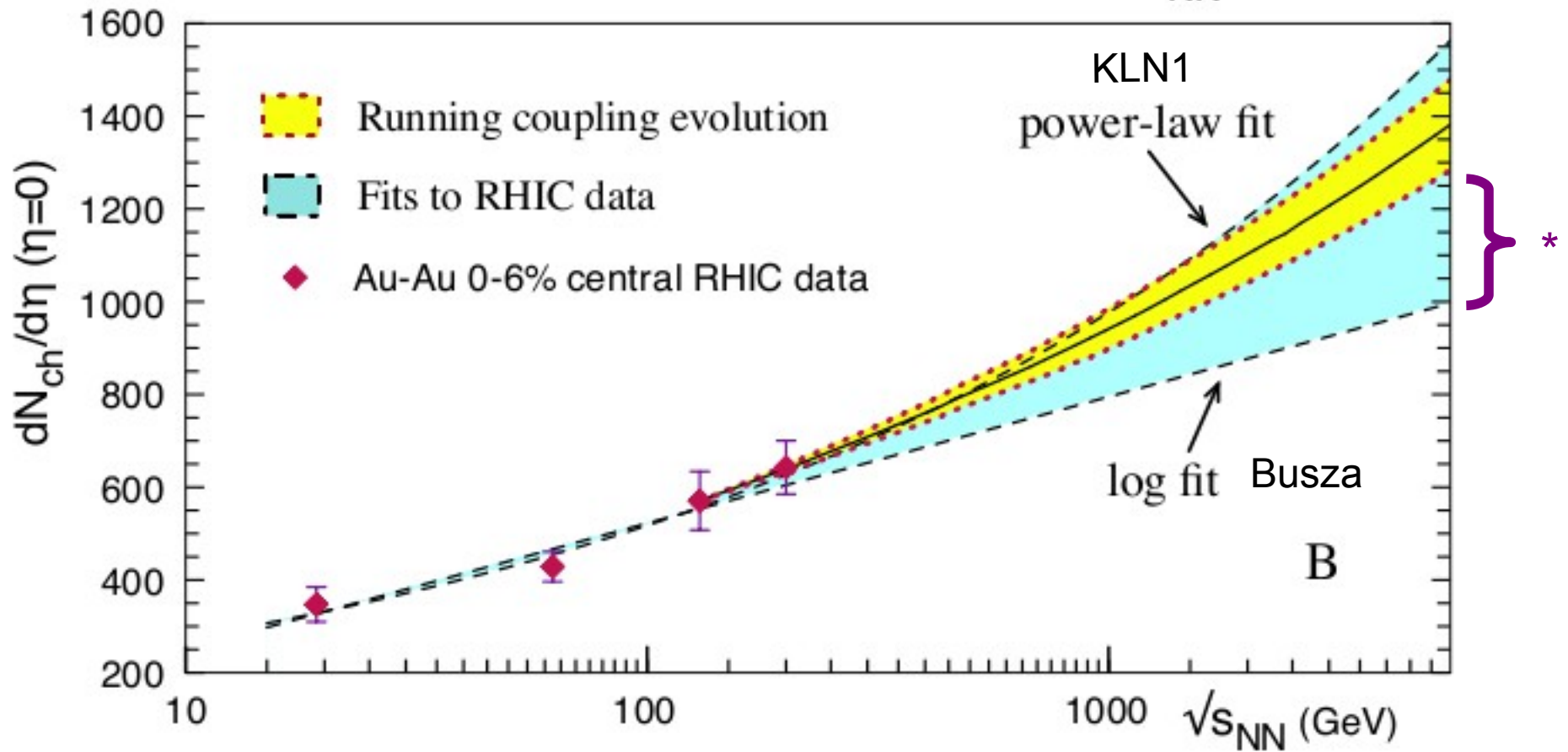


role of longitudinal color fields in parton evolution at small  $x$ , and found that they lead to the following dependence of the saturation momentum on rapidity [95]:

Super saturated?

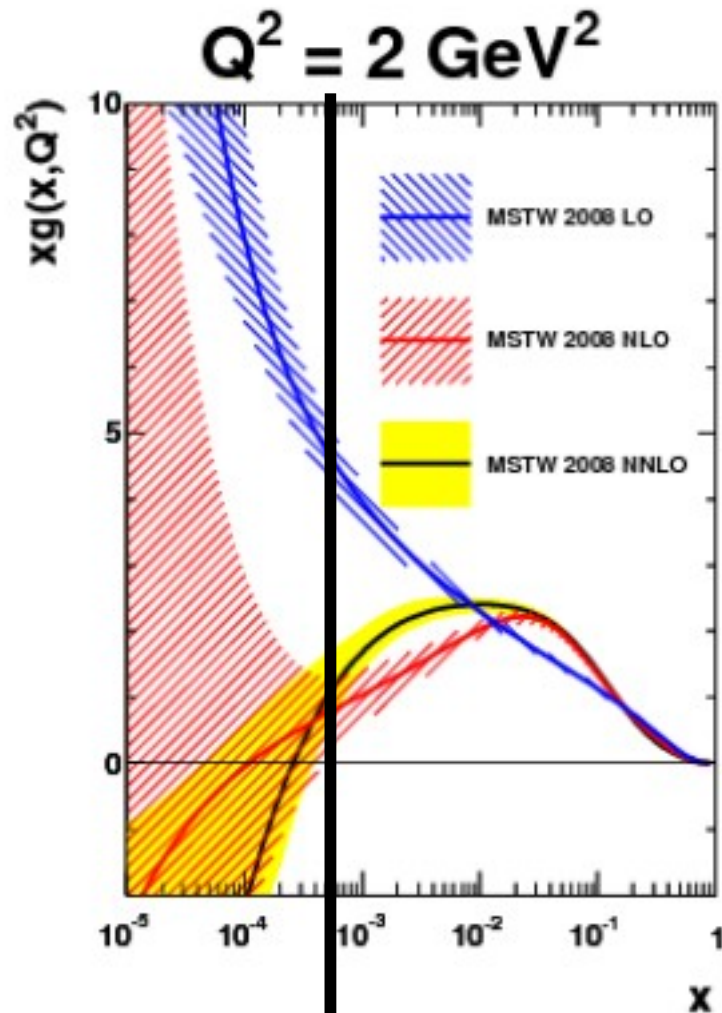
$$Q_s^2(Y) = \frac{Q_s^2(Y = Y_0) \exp\left(\frac{2\alpha_S}{\pi}(Y - Y_0)\right)}{1 + B Q_s^2(Y = Y_0) \left(\exp\left(\frac{2\alpha_S}{\pi}(Y - Y_0)\right) - 1\right)}, \quad < 1/B \quad (17)$$

\* Fujii et al  
fixed  $\alpha_f$  param



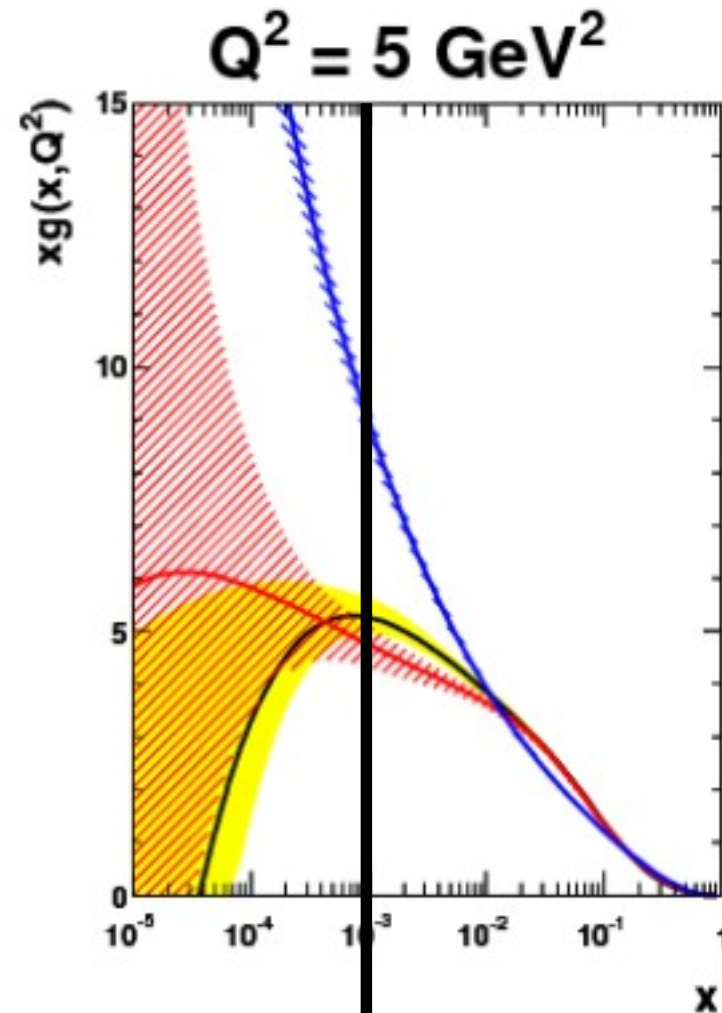
Why is CGC uncertainty so big when PDF now know to 5% (S. Forte) ??

Gluon structure MSTW 2008



5.5 TeV LHC

$Y=0, P_T=1 \text{ GeV}$



$Y=0, P_T=2 \text{ GeV}$

## MSTW 2008 Glue NNLO

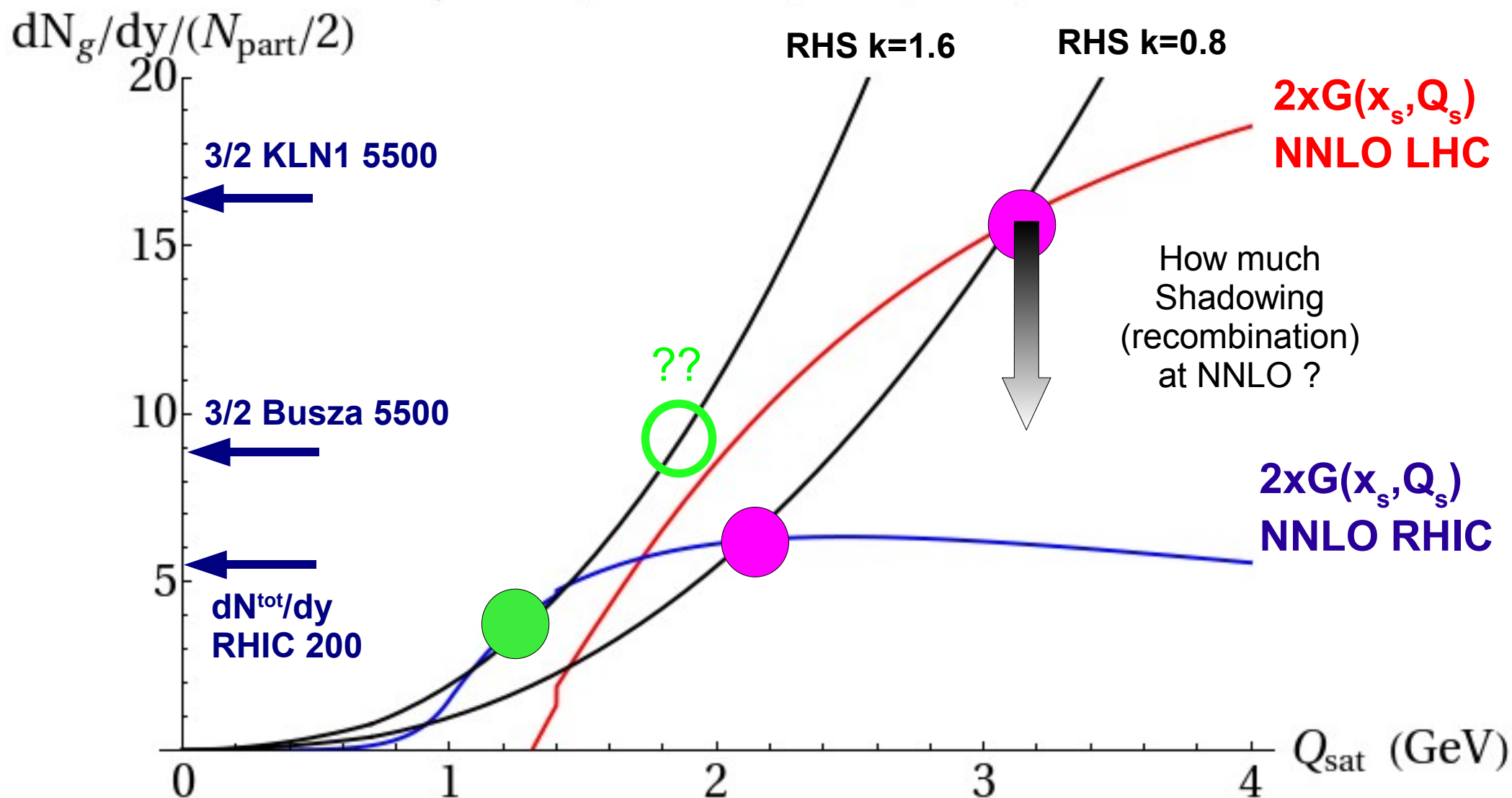
$$\frac{1}{A} \frac{dN_{\pi}^{\text{tot}}}{dy} =$$

Unshadowed PDF Driven CGC equation (JPB, AM 86)

$$dN_g/dy/(N_{\text{part}}/2) = 2 \times G(x_s = 2Q_s/s^{1/2}, Q_s^2) = k Q_s^2 R^2 / (\alpha(Q_s) A)$$

$$\sqrt{s} = 0.2, 5.5 \text{ TeV (RHIC, LHC)}$$

$$k = 1.6 / (\text{Gev} - \text{fm})^2$$



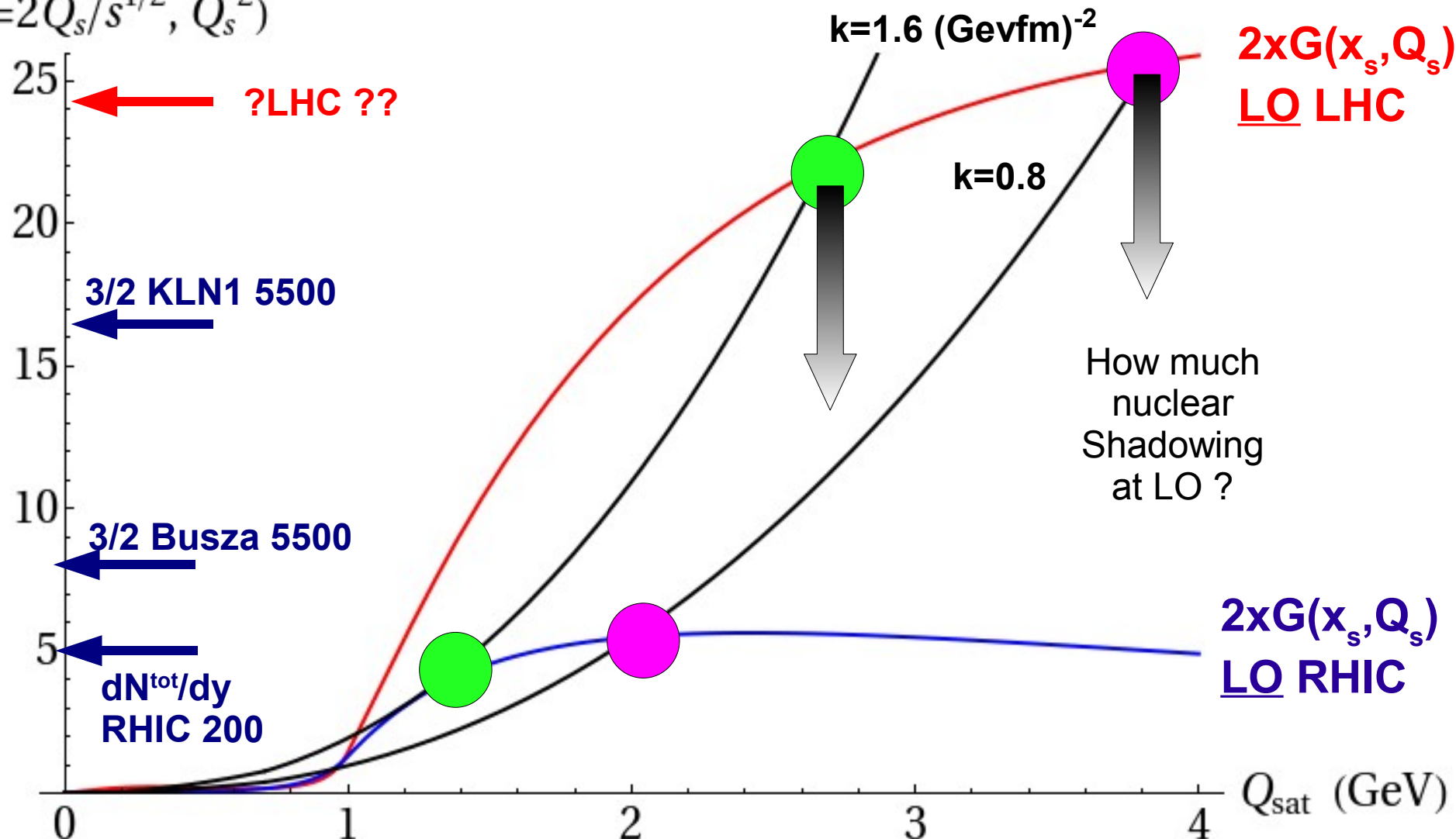
LO pdf driven CGC => much higher entropy  $dN^{\text{tot}}/dy \sim 5000$  ??

$$\frac{1}{A} \frac{dN_{\pi}^{\text{tot}}}{dy}$$

MSTW 2008 Glue LO

$\sqrt{s} = 0.2, 5.5 \text{ TeV (RhIC, LHC)}$

$$2 \times g(x = 2Q_s/s^{1/2}, Q_s^2)$$



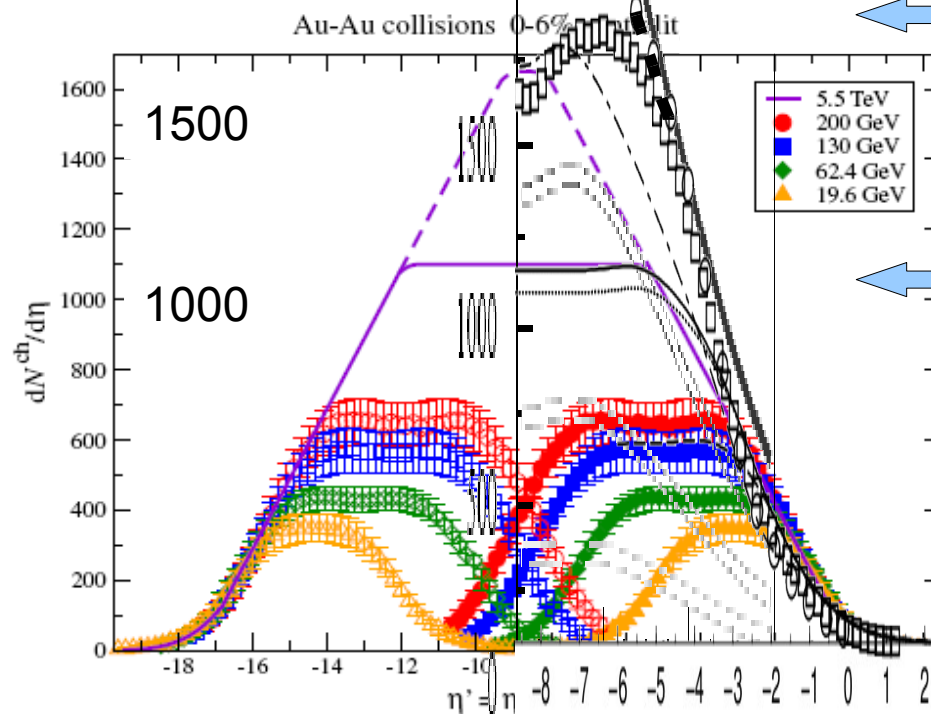
$$dN_g/dy / (N_{\text{part}}/2) = 2 \times G(x_s = 2Q_s/s^{1/2}, Q_s^2) = k Q_s^2 R^2 / (\alpha(Q_s) A)$$

**Day 1 at LHC**  
will set entropy scale

**Predictions for  
Bulk Entropy at LHC**  
 $\sim 6 dN_{ch}/dy$   
**vary by factor 3 !**

CGC  
kT factorized  
saturation

J. Phys. G: Nucl. Part. Phys. **35** (2008) 023001



HIJING1.37  
Multi-minijets  
 $p_0=3$  +ISR

EPOS  
Multi-pomeron

HIJING1.37  
Multi-minijets  
 $p_0=4$  (NO IFR)

Linear Log  
scaling

Borghini  
Wiedemann

Collinear fact. HIJING ~ Unshadowed PDF driven CGC

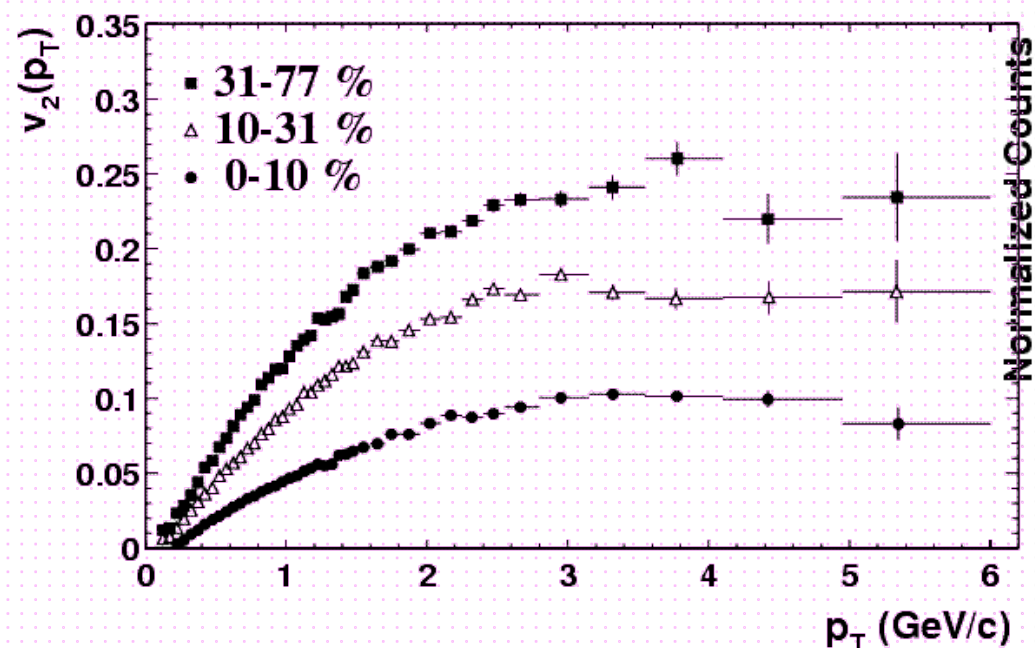
Part 2: From Perfect to Divine flow at LHC?

Will LHC kill perfect fluidity of the sQGP ?

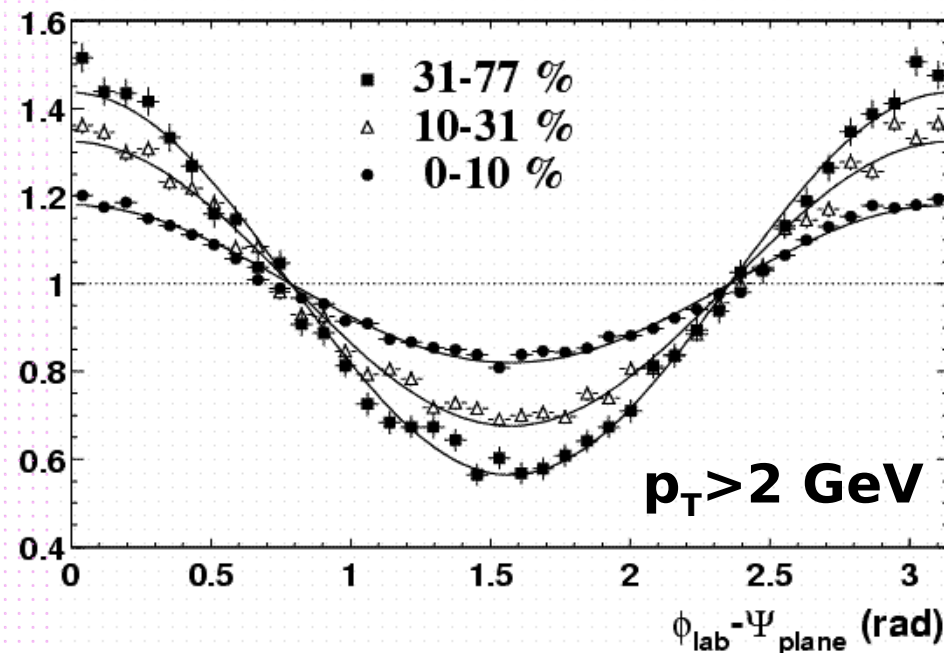
# Transverse Elliptic Flow in Non-central Au+Au at RHIC is the dominant Bulk probe

$$V_2 = \langle \cos 2(\phi_{lab} - \Psi_{plane}) \rangle$$

STAR 2002

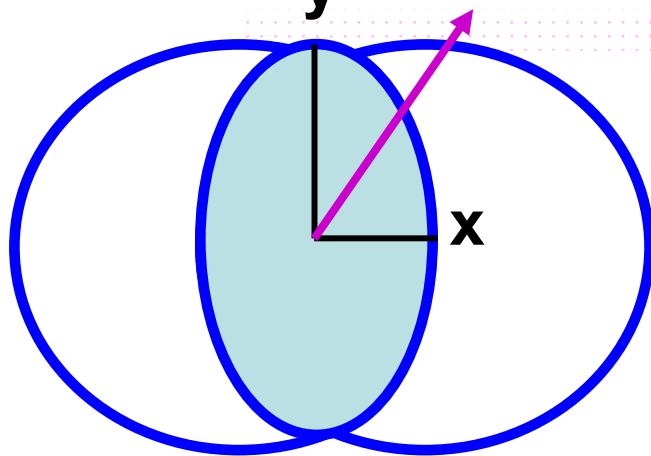


$$dN_{ch}(p_T, f - y_{reac})$$



Initial spatial anisotropy

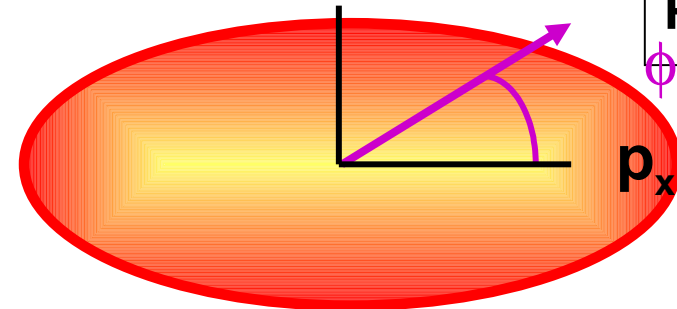
$z=0$



Final momentum anisotropy

$p_y$

$P_z=0$



$$\partial_\mu T^{\mu\nu}(x) \Rightarrow$$

Stoecker, Greiner 84, Ollitrault 92

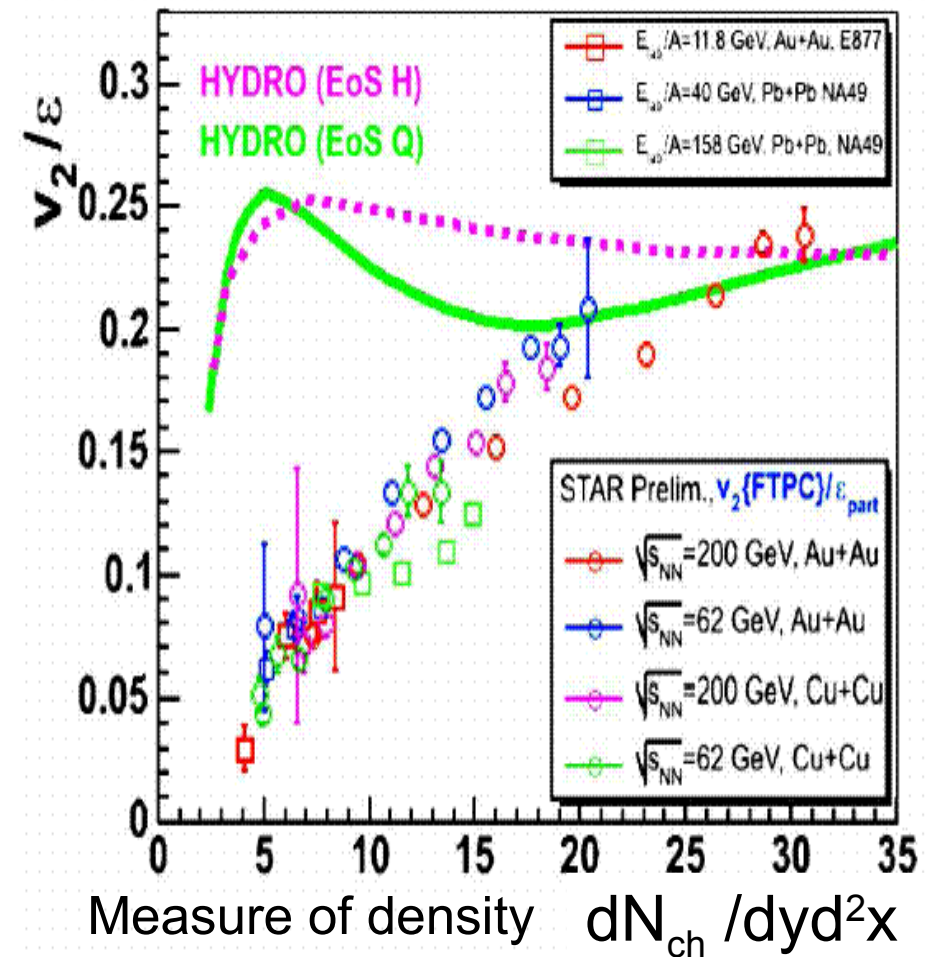
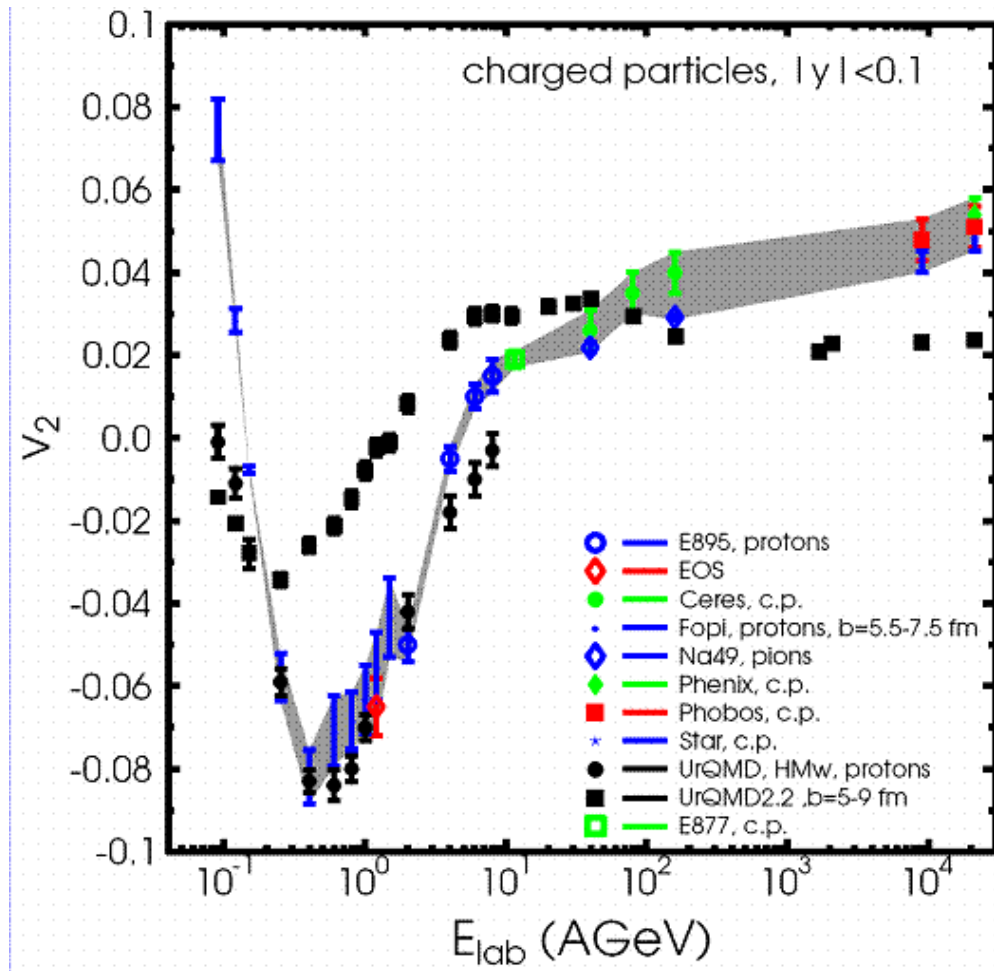
# Perfect Fluidity was first seen at RHIC energies

(Partial) Elliptic flow is everywhere

But Perfect fluid elliptic flow only at RHIC

M. Bleichert, et al UrQMD, Hadro Transport

Kolb, Heinz: Euler Hydrodynamics

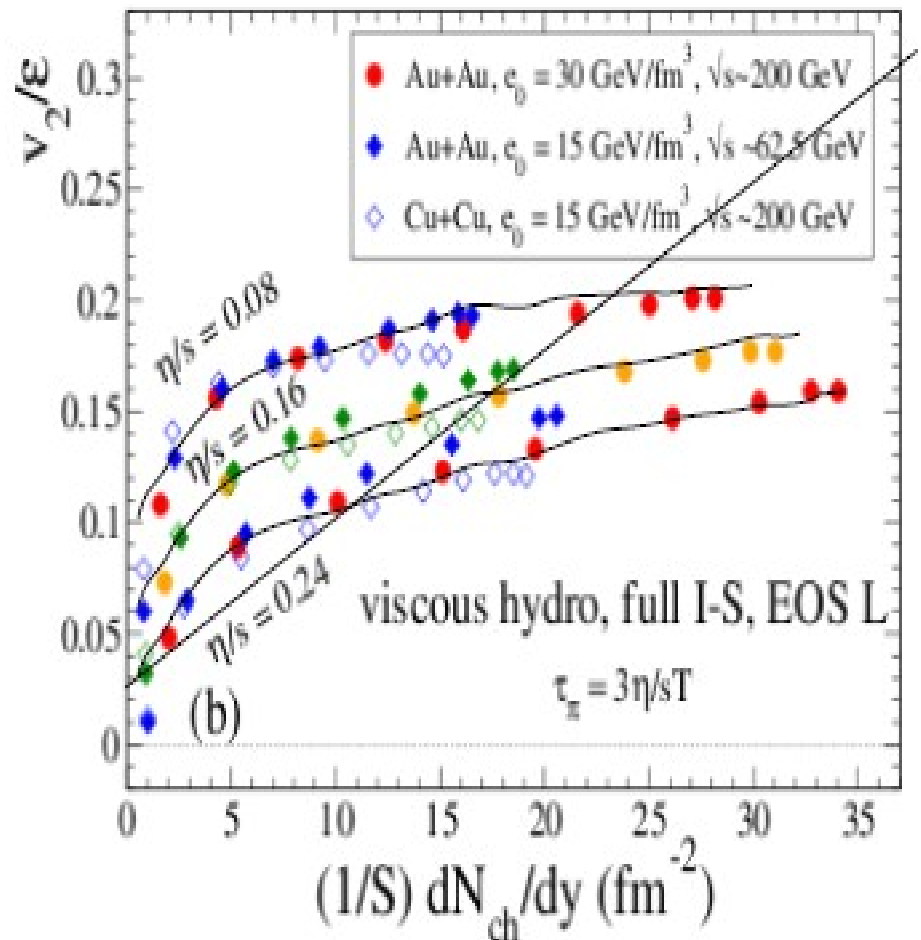
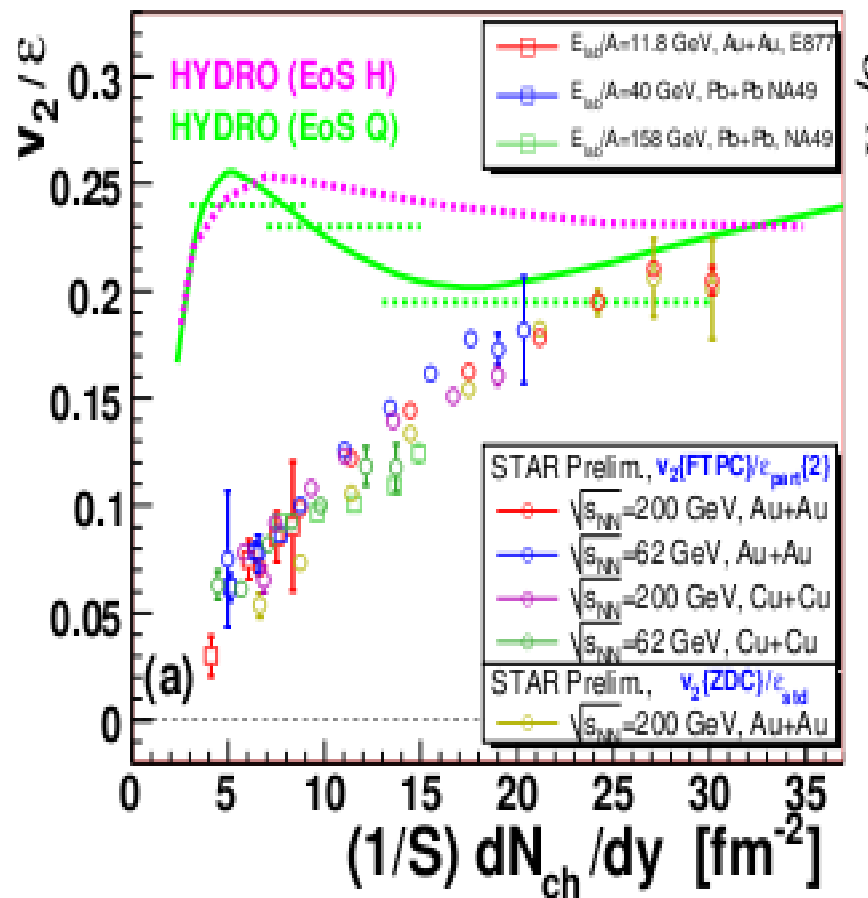


Ordinary nuclear matter and hadron resonance matter is a highly viscous fluid with large deviation from perfect fluidity while the sQGP appears to be nearly perfect at RHIC

Effective viscosity increases as density decreases

Classical gas  $\eta/s \sim T/(\sigma s)$

Heinz, Song 0901.4355



Entropy density (t)  $\sim 6 dN_{ch}/dy / (S t)$ , where S is participant transverse area

Beware!  
 $e_x$  is a  
 theory  
 number

Same  
 data  
 / two  
 different  
 geom  
 models

$$0.5 e_p/e_x (\approx v_2/e_x)$$

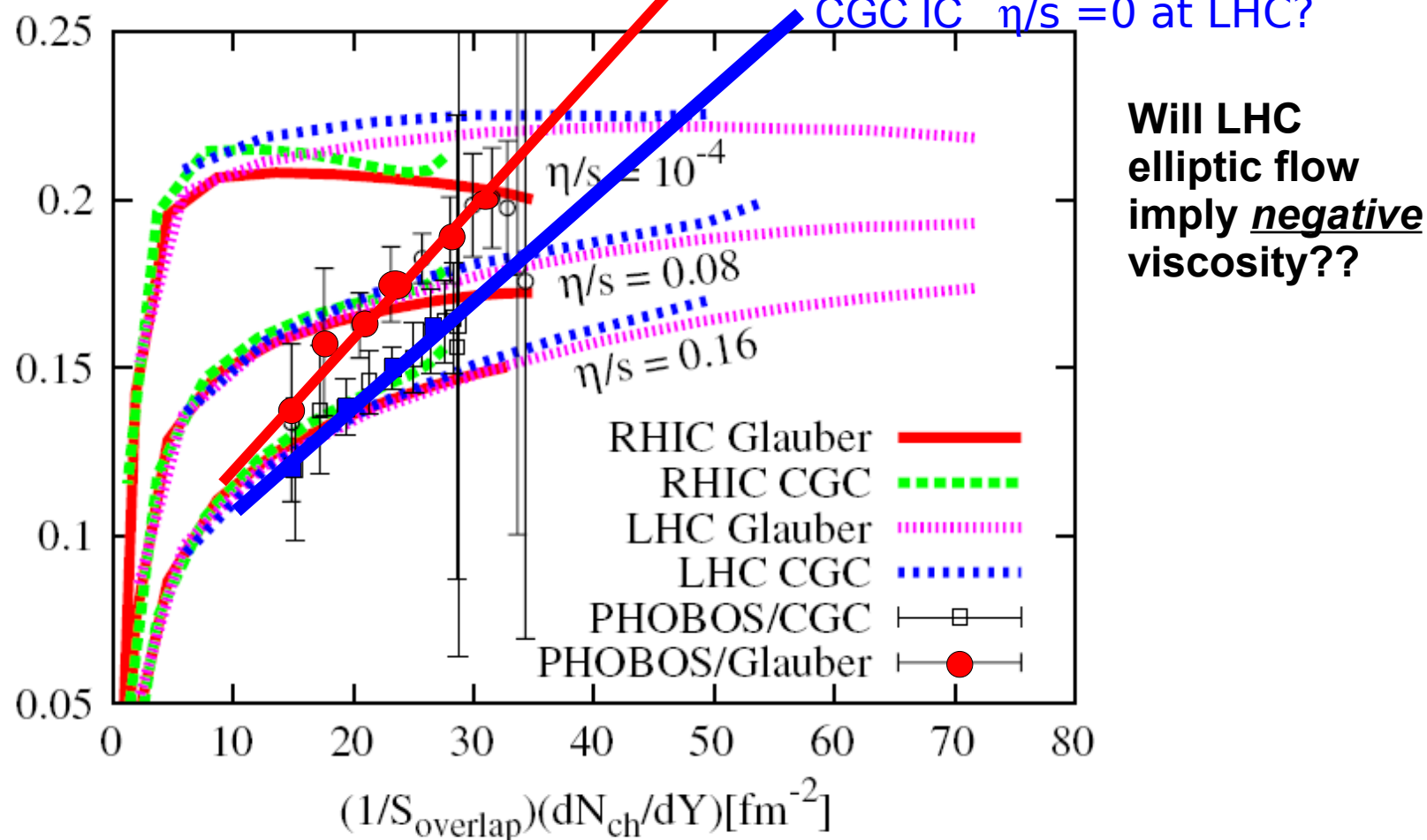


FIG. 1 (color online). Anisotropy (3) divided by (1), as a function of initial entropy (4) divided by (2). Shown are results from hydrodynamic simulations for  $\sqrt{s} = 200$  GeV Au + Au (RHIC) and  $\sqrt{s} = 5.5$  TeV Pb + Pb collisions (LHC). For comparison, experimental data for  $v_2$  from RHIC [38], divided by  $e_x$  from two models [13], is shown as a function of measured  $\frac{dN_{ch}}{dY}$

The SPS - RHIC  $v_2$  systematics suggests that  $v_2(\text{LHC}) > v_2(\eta/s=0)$

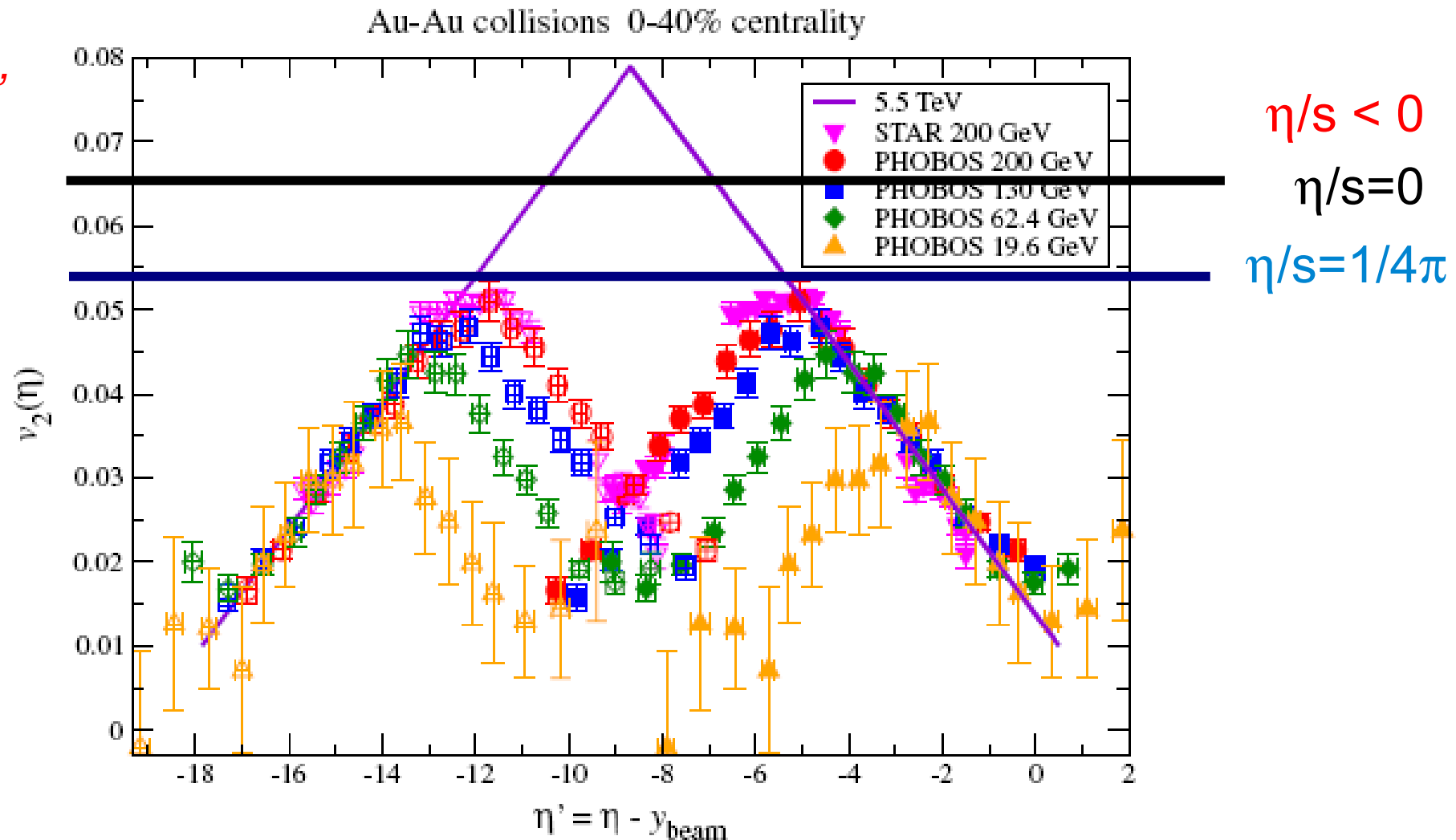
fluidity

*“Divine”*

ideal

Perfect :

lousy



**Figure 4.** The elliptic flow  $v_2$ , averaged over centrality (0–40%), at various collision energies. Data (full symbols) from PHOBOS [41] and STAR [42] are plotted as a function of  $\eta - y_{\text{beam}}$  and reflected (open symbols) across the LHC  $-y_{\text{beam}}$  value.

Elliptic flow with Pb+Pb at LHC  
could overthrow our  
current picture of the sQGP  
as a “as perfect as  $\hbar$  allows fluid”

The answer will be known after the  
first few  
thousand collisions!

### Part 3: What's Beyond perfect fluidity ? How can the sQGP bulk “corona” reveal novel early time matter

If LHC finds “divine” fluidity with  $\eta/s < 0$  via  $v_2(p_T)$

We will have to go back to  $t=0$  and try to blame the failure of hydro on a novel “third” component

So far no data except for a tiny  $10^{-4}$  enhancement of charged pair fluctuations (chiral magnetic effect) require such a third component

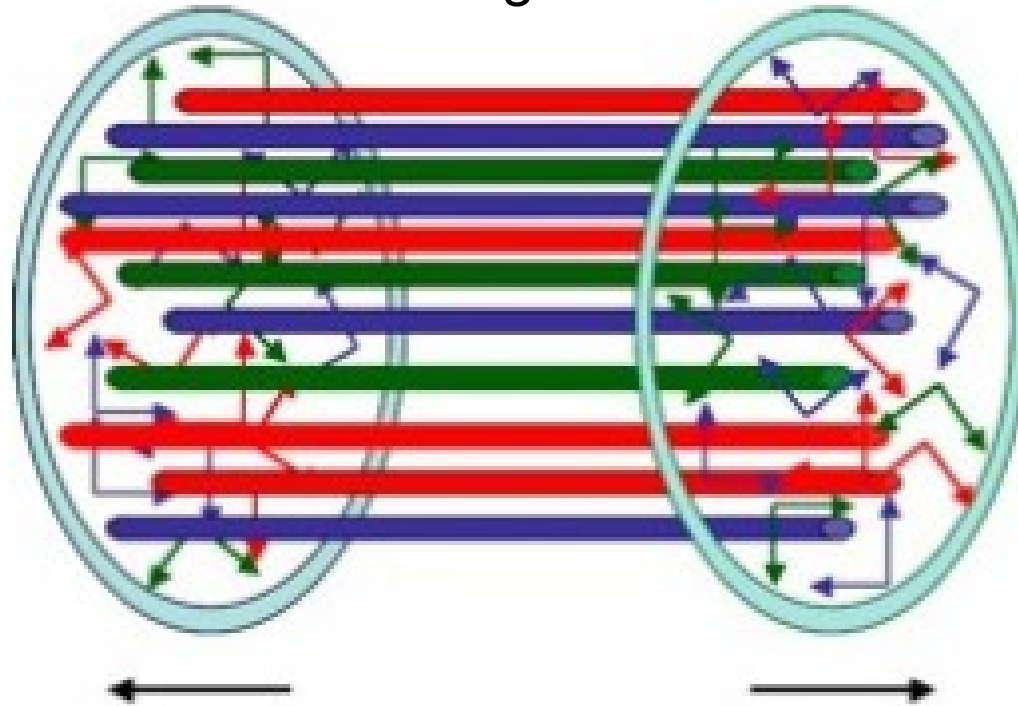
(Ridge correlations follow from Lund flux tube Fluctuations (F.Grassi) and are not unique to glasma.)

However, possible pre-equilib transverse expansion may be unique to glasma

Could this nonequilibrium YM configuration drive the Bulk to divine flow ?

“Glasma” = Classical Yang-Mills field dominated  $V > KE$

L. McLerran  
arXiv:0812.1506



Like 30 year old  
Lund Flux Model  
Anderson et al

But Glasma also  
has magnetic  
flux tubes

and a transverse  
area  $1/Q_{\text{sat}}(s,A)$

Compared to the sQGP matter dominated with  $KE > V$

sQGP= strongly coupled QCD equilibrated “fluid” with  
anomalously small dissipation compared to wQGP

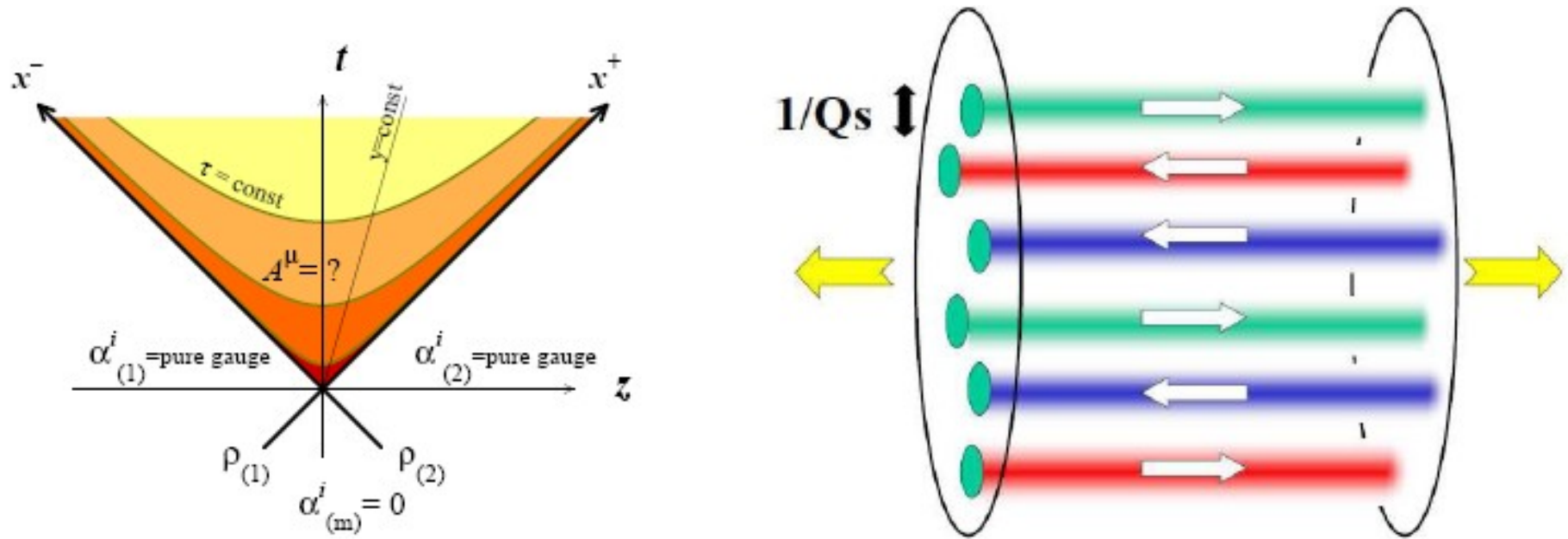
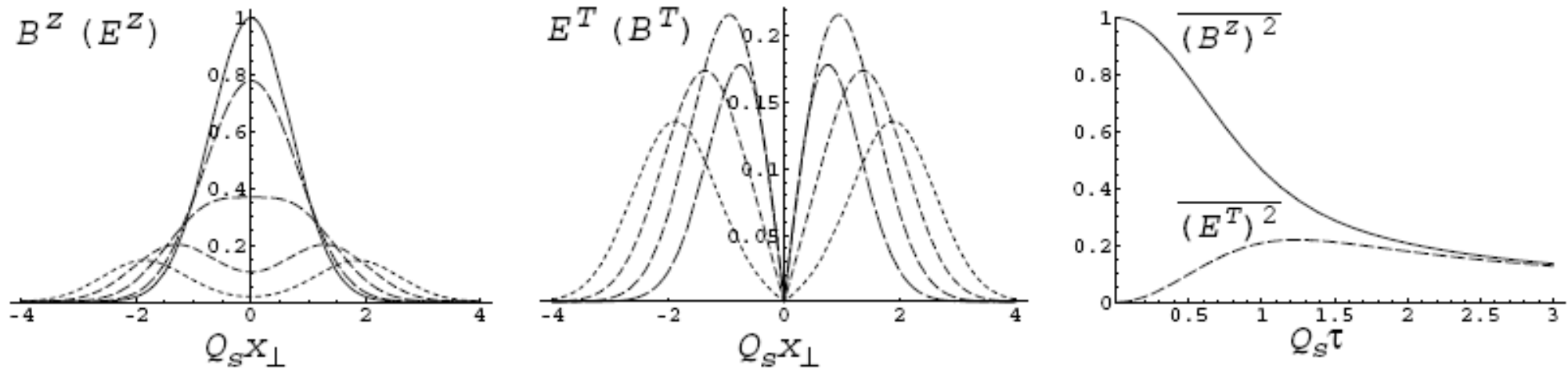


FIG. 1: Event setup (left) and schematic picture (right) of the color electric and magnetic flux tubes with transverse size  $1/Q_s$ , created between the two Lorentz-contracted nuclei just after the collision.

Here we use the Fock-Schwinger gauge,  $\mathcal{A}_\tau = 0$ . The corresponding initial field strengths are

$$E^z|_{\tau=0+} = -ig[\alpha_1^i, \alpha_2^i], \quad B^z|_{\tau=0+} = ig\epsilon_{ij}[\alpha_1^i, \alpha_2^j]. \quad (3)$$

The ideal Glasma flux tube YM Solutions expand radially  
 equilibrate on fast  $1/Q_s < 1$  fm time scales



The Glasma transverse expansion could give the sQGP fluid an **initial radial boost** to seed “apparent elliptic flow” beyond the zero viscosity limit at LHC. The bulk sQGP could then serve as a detector of the Glasma

(Work in progress by R. Venugopalan et al)

Part 4: Will the CGC at LHC negate jet tomography?

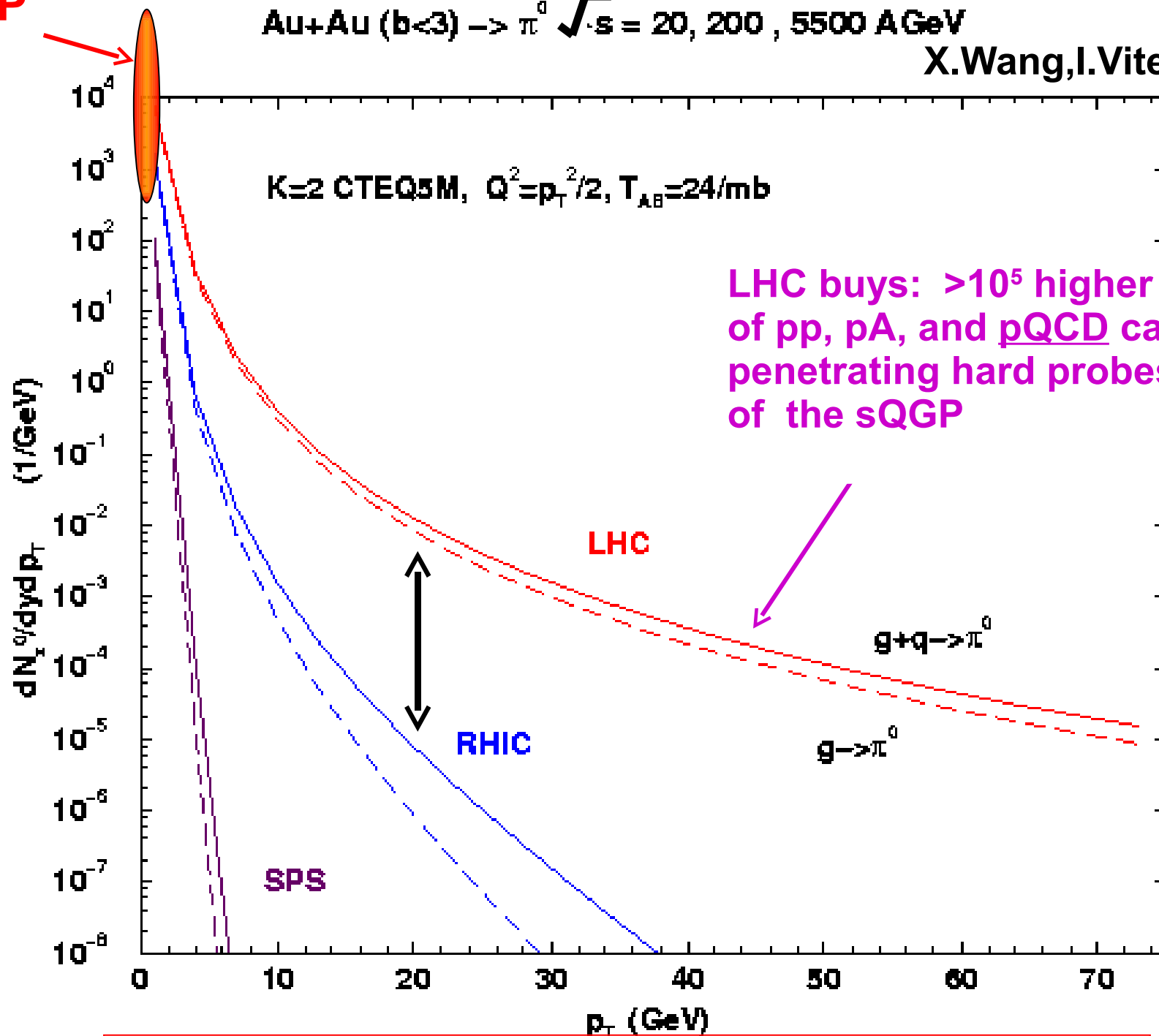
LHC will certainly produce copious jets out to 100 GeV

How can we deconvolute initial state suppression from final state QCD or AdS Holographic energy loss?

**sQGP**  
 **$p_T < 2$**

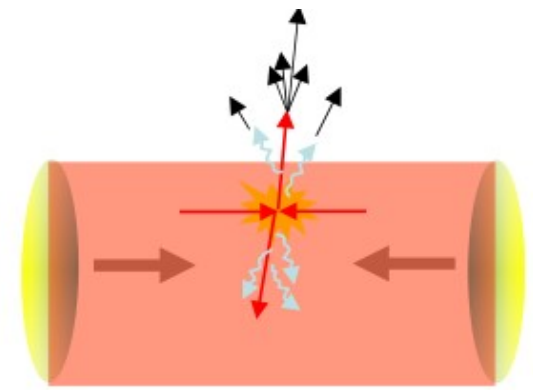
**Au+Au ( $b < 3$ )  $\rightarrow \pi^0$   $\sqrt{s} = 20, 200, 5500$  AGeV**

**X.Wang, I.Vitev, MG**

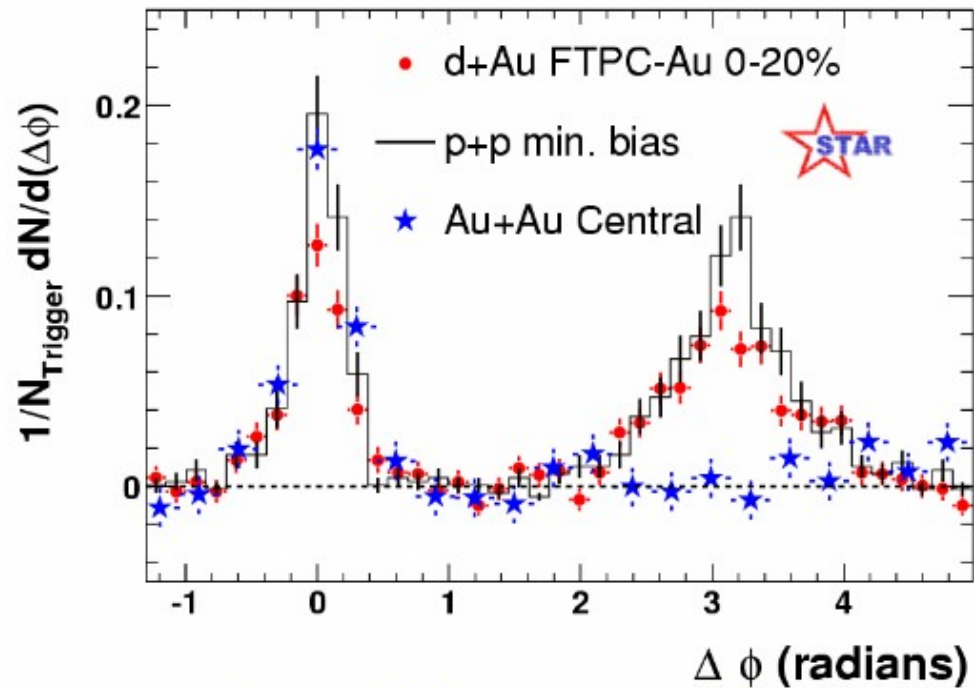


**High  $p_T$  “hard” observables can probe the “soft” sQGP**

At RHIC Jet quenching  
was the second major discovery  
(as predicted MG, XNWang PRL 1992)



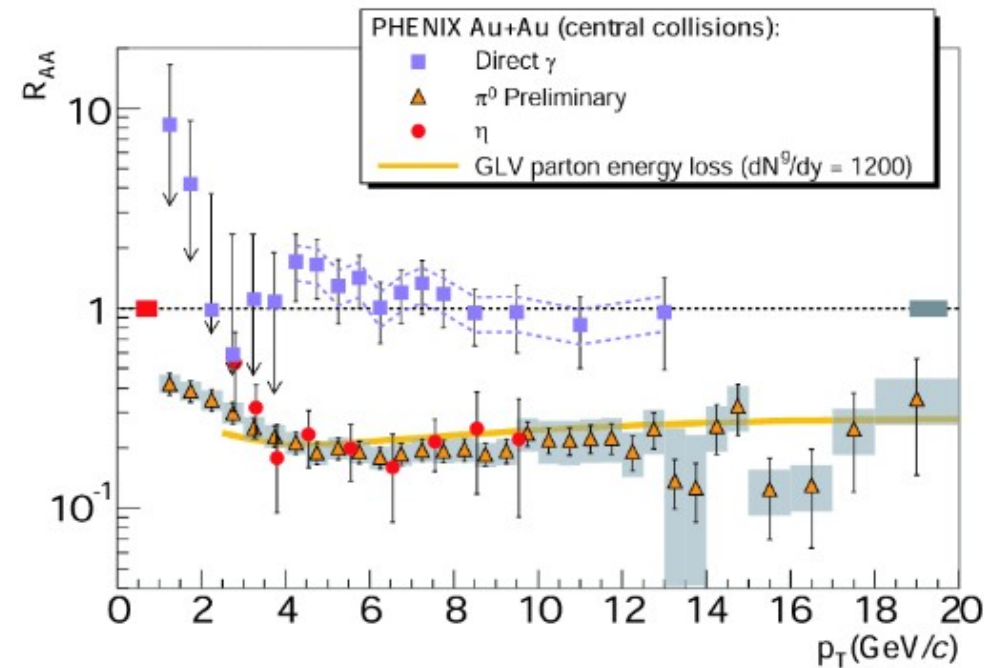
$$R_{AA} = dN_{AA} / A^{4/3} dN_{pp}$$



Away side suppression

$$4 < p_T(\text{trig}) < 6 \text{ GeV/c}$$

$$p_T(\text{assoc}) > 2 \text{ GeV/c}$$



PHENIX

In contrast, at LHC some CGC predicts large suppression even in p+A !!

**Absence of Suppression in Particle Production at Large Transverse Momentum  
in  $\sqrt{s_{NN}} = 200$  GeV d + Au Collisions**

E

PHENIX

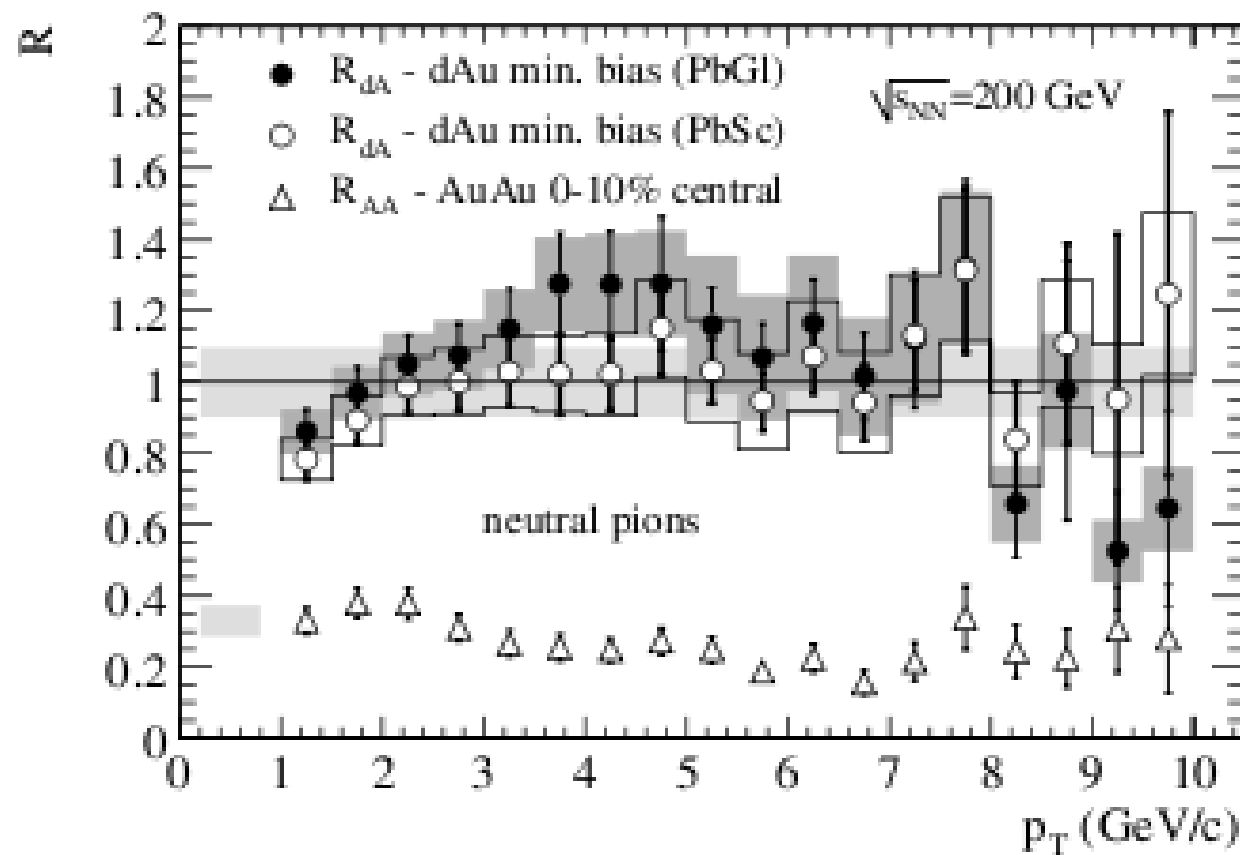
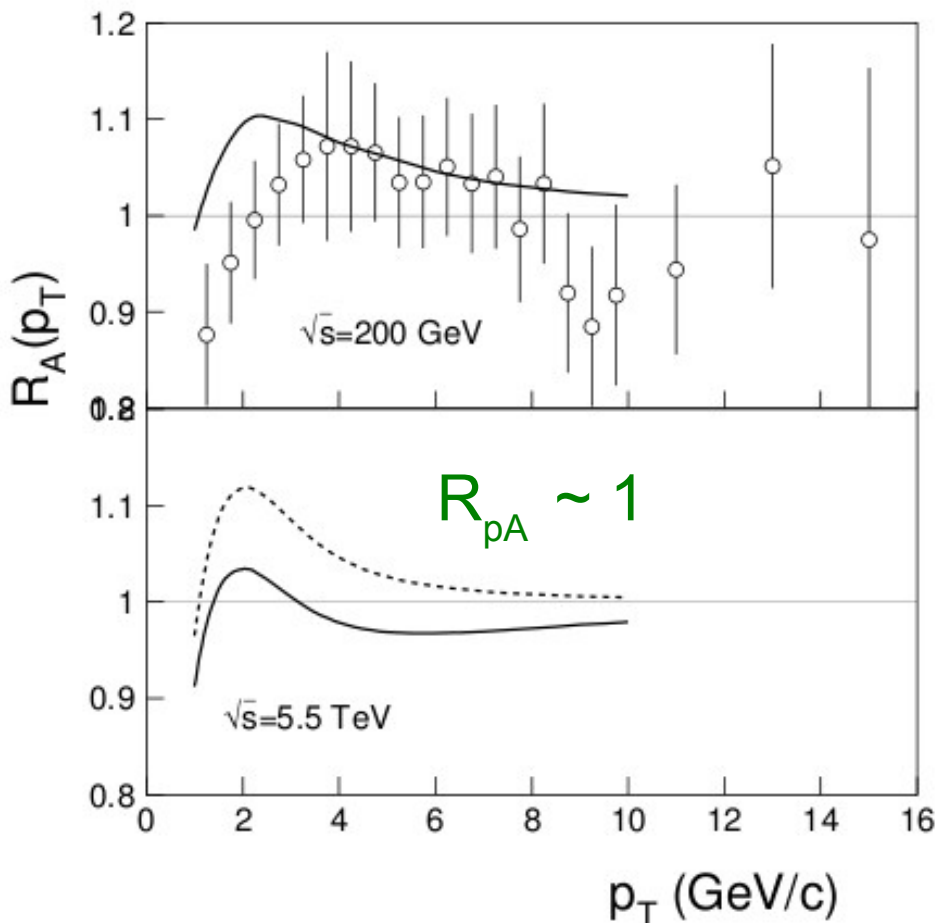


FIG. 2. Nuclear modification factor  $R_{dA}$  for  $\pi^0$  in the PbGl

## 1.19. CGC at LHC

B. Kopeliovich and I. Schmidt

Predicts similar weak  $y=0$  as at RHIC

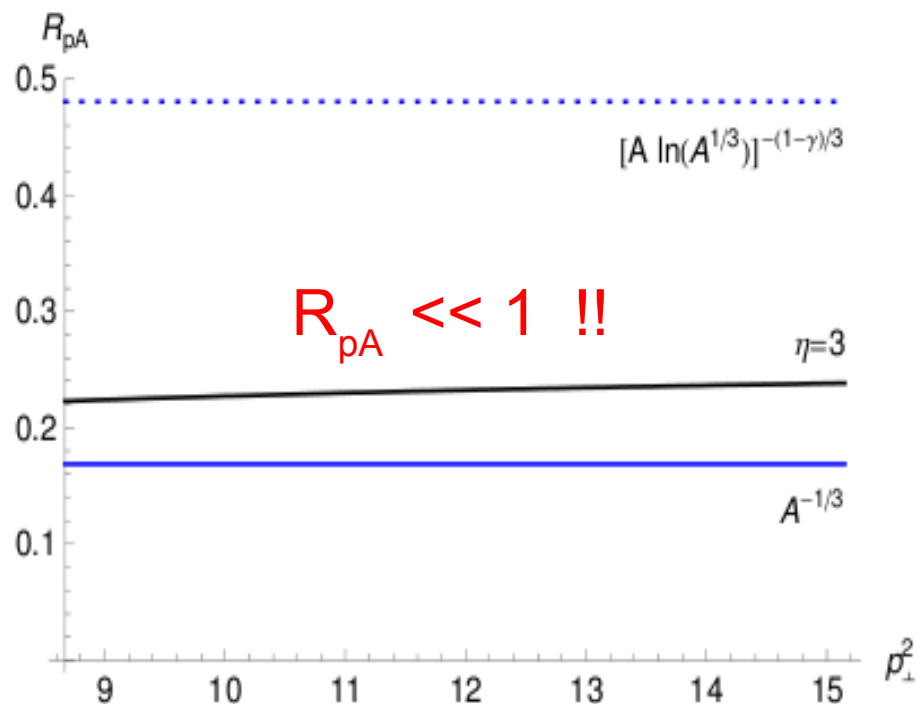


Assumes small  $r \sim 0.3$  clustering  
 $\Rightarrow$  dilute overlap  
 $\Rightarrow$  can use RAA for FSI tomography

## 1.16. $R_{pA}$ ratio: total shadowing due to running coupling

E. Iancu and D. N. Triantafyllopoulos

Predicts maximal shadowing



$\Rightarrow$  AA FSI quenching would be impossible to deconvolute from Initial State Shadowing until  $p+A$  is fully understood

Is this the  
falsifiable test  
of BK evolution?

What if it fails?  
Is there wiggle  
room?

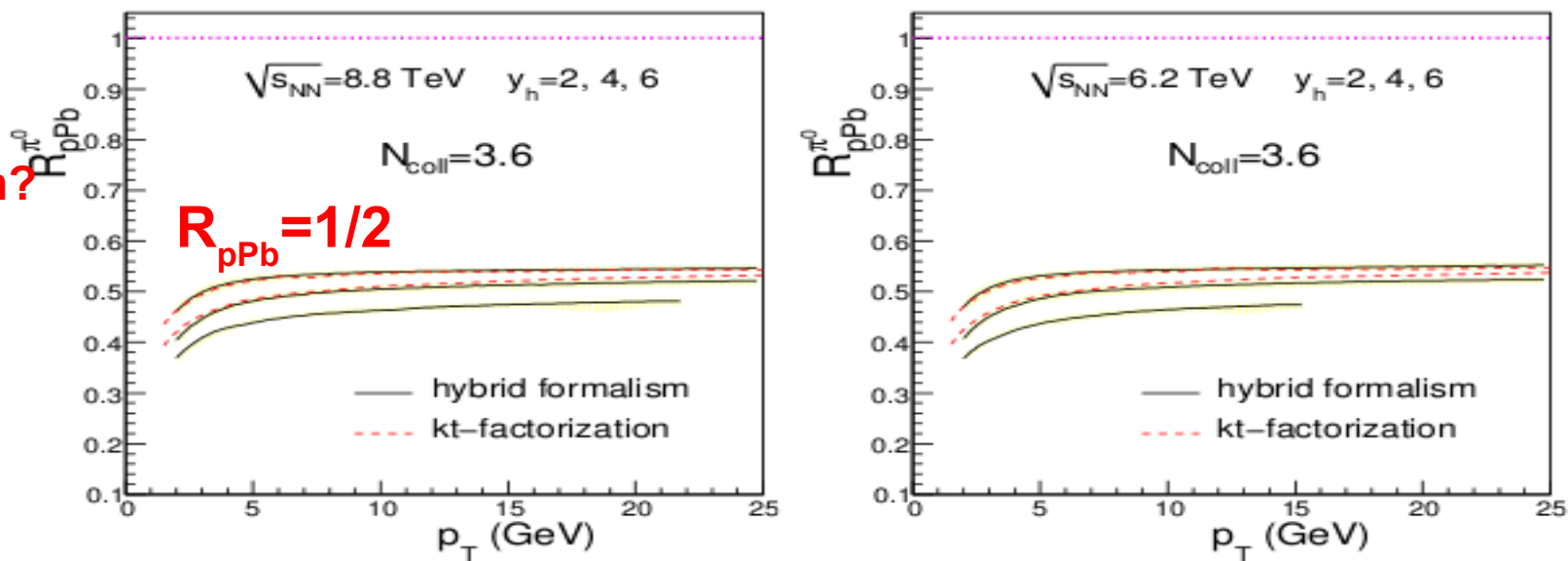


Figure 2: Nuclear modification factors for  $\pi^0$  production in p+Pb collisions,  $R_{pPb}^{\pi^0}$ , for collision energies  $\sqrt{s_{NN}} = 8.8$  (left) and 6.2 TeV (right) and for rapidities  $y_h = 2, 4$ , and 6. For comparison, the red dashed line corresponds to the same quantity calculated in the  $k_t$ -factorization scheme.

Note AdS/CFT  
Also Predicts this  
extreme quenching

Horowitz, MG

How to untangle BH  
from saturated fields?

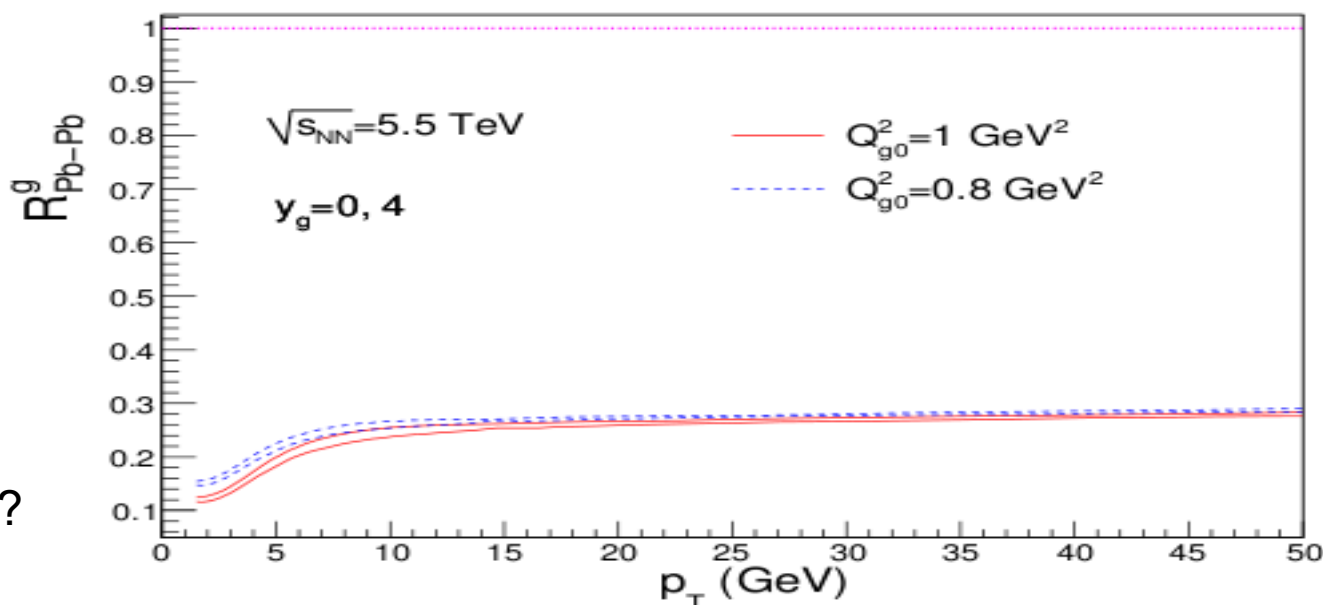
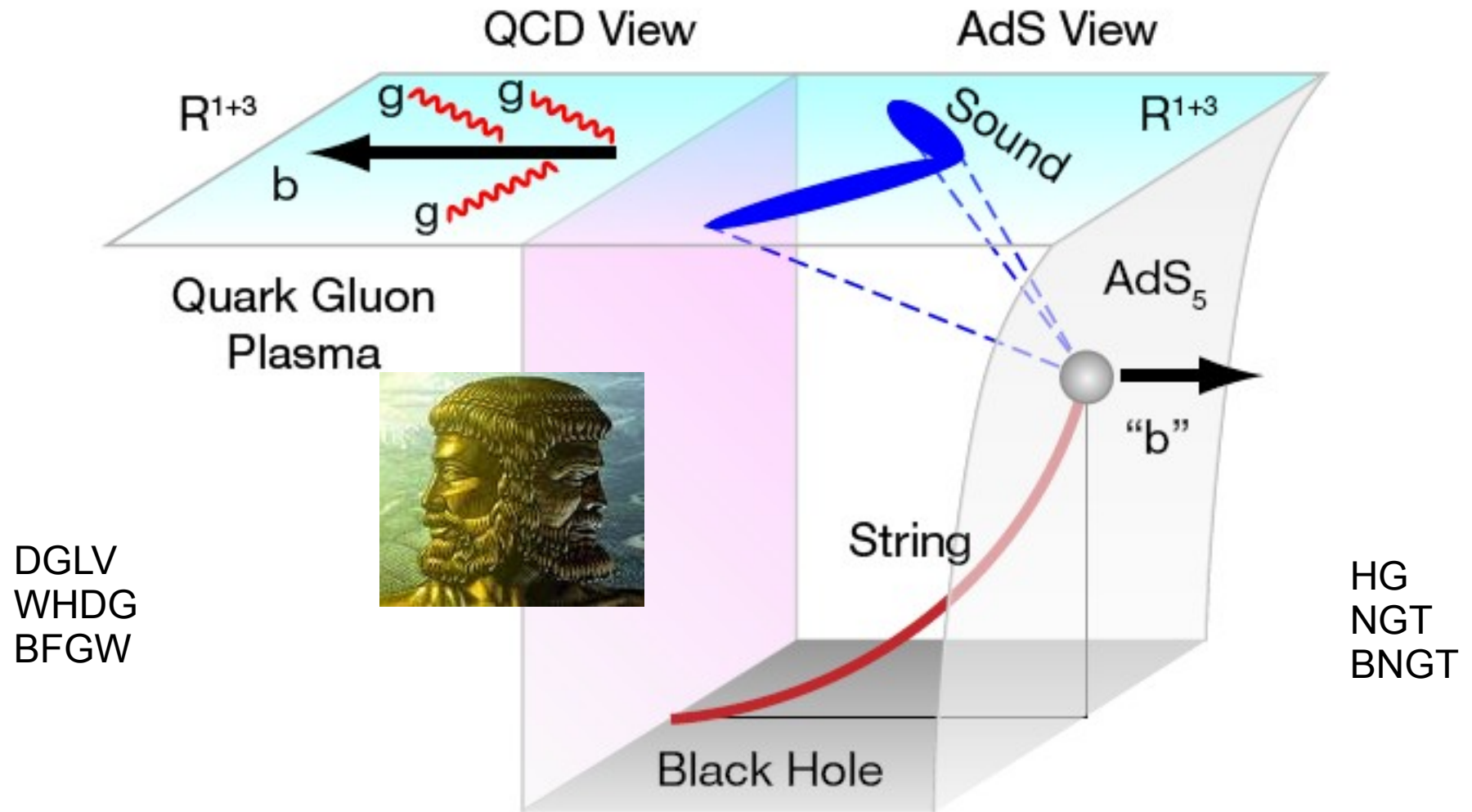


Figure 4: Gluon level predictions from  $k_t$  factorization for Pb+Pb collisions for rapidities  $y = 0, 4$ . Solid lines correspond to an initial gluon saturation scale  $Q_{s0}^{gluon\ 2} = 1$  GeV<sup>2</sup>, and the dashed ones

**Getting to the bottom of the heavy quark jet puzzle** *Physics 2*, 107 (2009)  
Bottom Quark Jet Quenching



**Will Janus require a third face toward CGC to help unravel anomalous heavy quark quenching at LHC ?**

# Open LHC QCD Matter Challenges

Part 1: LHC initial conditions are hard to predict because quantal CGC is nonlinear physics, sensitive to boundary conditions. But without accurate IC bulk sQGP flow, Jet Quenching etc cannot be inverted.

Part 2: Perfect Fluidity at RHIC may become “Divine Fluidity” with apparent  $\eta/s < 0$  on day 1 at LHC

Part 3: Divine flow could be the signature of Glasma prequilibrium transverse flow. Urgent need for numerical predictions for both RHIC and LHC

Part 4: Jet tomography will require extensive p+A studies to enable deconvolution of initial and final state physics

the LHC butcher block awaits our predictions